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Life Cycle Analysis of a Game-Based Solution for Domestic Energy Saving

Marta Gangolells *, Miquel Casals, Núria Forcada and Marcel Macarulla

Group of Construction Research and Innovation (GRIC), Department of Project and Construction Engineering, Universitat Politecnica de Catalunya, 08222 Terrassa (Barcelona), Spain; miquel.casals@upc.edu (M.C.); nuria.forcada@upc.edu (N.F.); marcel.macarulla@upc.edu (M.M.)

* Correspondence: marta.gangolells@upc.edu; Tel.: +34-93-7398947

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Abstract: ICT-based solutions are seen to be almost totally environmentally friendly, but game-based solutions for energy saving have not been explored yet. This paper describes a comprehensive analysis and an in-depth interpretation of the life cycle environmental impact of a game-based solution for domestic energy saving, developed and validated within the EU-funded Horizon 2020 project EnerGAware—Energy Game for Awareness of energy efficiency in social housing communities. Life cycle impacts were calculated with SimaPRO 8.5.2.0 using the ReCiPe 2016 v1.02 midpoint and endpoint methods and information contained within the Ecoinvent v3.4 database. Although the pre-competitive solution, directly arising from the research project, was found to have a relatively high environmental impact, its future exploitation, which mostly relies on existing infrastructure, was found to be highly competitive from an environmental perspective. The game will help reduce the life cycle impact of domestic energy consumption on damage to human health (3.68%), ecosystem quality (3.87%), and resource availability (4.81%). Most of the environmental impact of the market solution was found in the manufacturing phase (77.96–80.12%). Transport (8.86–7.57%), use (3.86–5.82%), and maintenance (7.24–7.54%) phases were found to contribute little to environmental impact. This research provides a useful reference for decision-making as it contributes to the environmental benchmarking of competing energy-saving strategies.

Keywords: serious game; environmental impacts; life cycle assessment; social housing

1. Introduction

The Paris Agreement has accelerated the European Union's efforts to decarbonise its building stock. Within this context, the new Directive 2018/844/EU amending the Energy Performance of Buildings Directive [1] enhances the transformation of existing buildings into nearly zero-energy buildings by shifting to more sustainable energy supplies, implementing deep retrofitting strategies, and using ICTs (information and communication technologies) to improve energy performance. Within this last field, several ICT solutions have been developed for collecting data and controlling building systems. Improving end-users consumption behavior has lately emerged as a cost-effective strategy for reducing wasted energy in buildings [1–6], and therefore several solutions aimed at exploring the potential introduced by various novel ICTs to design effective energy efficiency systems [6] based on raising users' energy awareness and promoting behavioural changes [7] have been recently developed. Among others, gamification has emerged as a tool for increasing residential customers' engagement in energy efficiency [8]. Himeur et al. [6], Pasini et al. [7], AlSkaif et al. [8], Morganti et al. [9], Johnson et al. [10], Boomsma et al. [11], Ouariachi et al. [12], Csoknyai et al. [13] and Ponce et al. [14] provide an extensive review of relevant existing initiatives with various levels of success.

In this area, the European research project EnerGAware—Energy Game for Awareness of energy efficiency in social housing communities [15] developed and successfully validated an innovative game-based solution called Energy Cat: the House of Tomorrow [16] to promote reduced energy consumption by increasing tenants' understanding and engagement.

Energy Cat: the House of Tomorrow [16] is a serious game available for both Android and iOS tablets that lets players create their own virtual home and learn about potential energy savings due to installing energy-efficiency measures and changing user behaviour, whilst maintaining comfort (Figure 1). The player controls the Energy Cat, and his intervention is necessary to keep humans living in the house on the environmental right track. Game mechanics rely on three main parameters: energy points, happiness and money. Energy points diminish according to the energy consumption of the virtual house. Implementing energy saving measures or changing humans' behaviour allows the player to gain saving energy points, which can be later used to unlock new game content such as house furniture and decorative items but also energy efficient upgrades for the house. Happiness depends on the comfort achieved in the house. Money, earned by the humans living in the house, is used to buy items that have been previously unlocked. Happy humans earn more money to prevent players from not providing comfortable conditions of habitability to save energy points (i.e., not heating the house in winter). Missions gradually unfold in the game and help players to learn how to play the game and to acquire energy efficient habits [17]. The game is linked to real household energy consumption data. Savings in the real world are translated into in-game currency, providing immediate rewards and unlocking new features in the game (Figure 1).

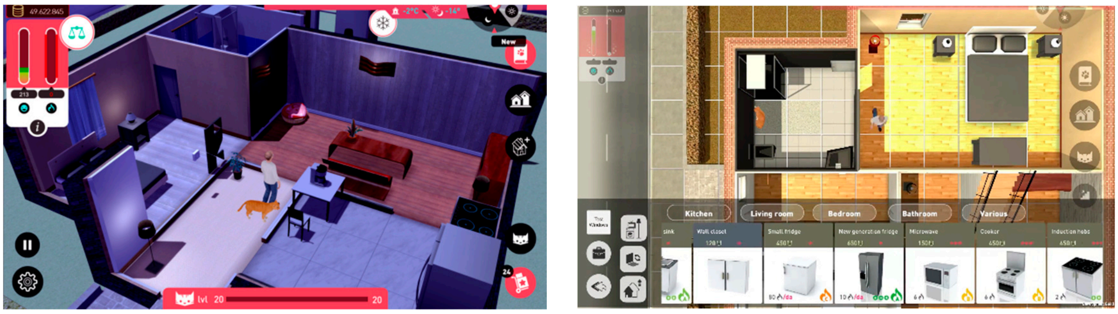

Figure 1. Energy Cat: the House of Tomorrow. Source: Energy Cat [16].

The game was validated using a cohort of 100 social houses in Plymouth (UK). To assess the impact of the EnerGAware intervention, houses were randomly assigned to the experimental or the control group. Social housing tenants in the experimental group played the game and had their energy (gas and electricity) consumption monitored. Social housing tenants in the control group did not play the game but still had their energy consumption monitored. Using the pre-post comparison approach, energy consumed by the houses in the experimental group before (during the baseline period) and after (during the reporting period) the implementation of the game was compared. The energy consumed by the houses in the experimental group was also compared with that of the houses in the control group during the reporting period. Houses in the pilot were found to have a median consumption of 9.08 kWh_s/day·house of electricity and 14.10 kWh_s/day·house of gas during the baseline period [18]. After implementation of the game and in the reporting period, weather-corrected energy savings were found to amount to an average of 5.34% of energy consumed in the long-term, with savings of 3.46% for electricity and 7.48% for gas. Further details regarding the EnerGAware project and the obtained results are available from Casals et al. [19].

Generally, ICT products and services are seen to be almost totally environmentally friendly (i.e., e-commerce, videoconferencing, intelligent energy management systems, etc.). With the rapid adoption of digital technologies, resources needed to manufacture and power ICT devices and operating infrastructure have become a significant source of greenhouse gas emissions, leading to the aggravation of climate change and its potentially devastating effects [20]. Therefore, although preliminary results support the utility of gaming investment in the household energy efficiency field [19], it is of utmost importance to explore the environmental consequences these kind of ICT-based approaches may entail during all life cycle stages.

While there have been many studies about life cycle environmental impacts within the ICT industry, ICT-based energy saving technologies have not been explored enough. Existing initiatives [21–27] have mostly focused on building energy management systems. To the authors' knowledge, no previous research has attempted to ascertain the life cycle impact of game-based solutions for energy saving.

Thus, the main objective of this paper is to examine the range of environmental impacts related to the commissioning and usage of a game-based solutions for domestic energy saving, developed within the EU-funded Horizon 2020 project EnerGAware—Energy Game for Awareness of energy efficiency in social housing communities [15]. This paper also examines whether game-based solutions improve or worsen the environmental impact of the overall system. For this reason, the paper compares environmental impact related to the energy consumption of houses in the pilot study during the baseline period (before implementation of the game) with that of the reporting period (after implementation of the game), including the entire life cycle impact of both the game and the energy consumed (Figure 2). This paper analyses two scenarios: the pre-competitive solution, directly arising from the research project, and the market solution, considering the future exploitation of the game. Section 2 details the methodology and Section 3 discusses the obtained results. Finally, conclusions and future research are outlined in Section 4.

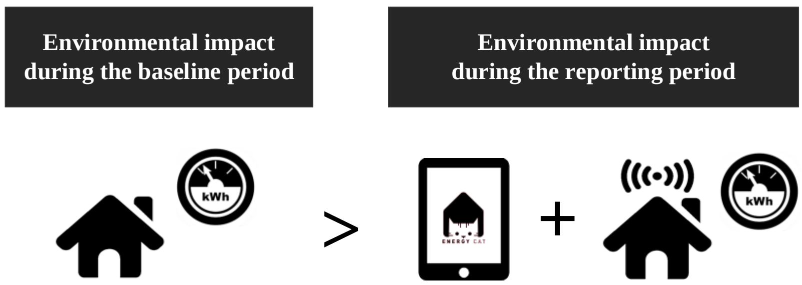

Figure 2. Hypothesis to be compared. Source: own elaboration.

2. Methodology

As shown in Figure 3, the methodology used in this research follows ISO standards on life cycle assessment, namely ISO 14040 [28] and ISO 14044 [29].

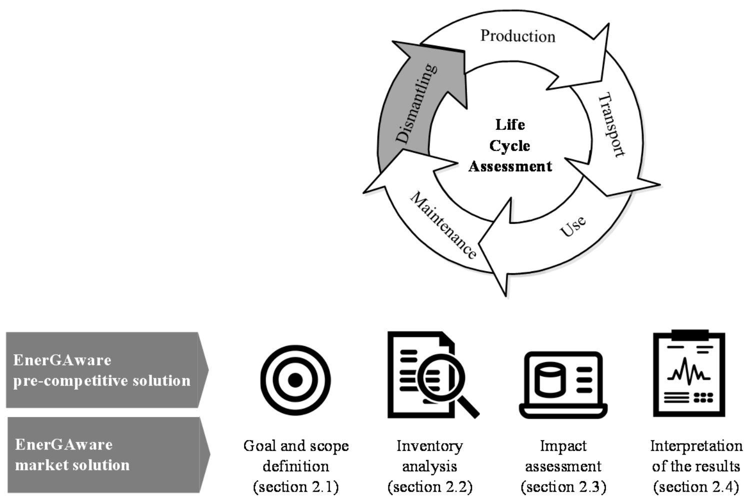

Figure 3. Methodology. Source: adapted from ISO 14040 [28] and ISO 14044 [29].

2.1. Goal and Scope Definition

The goal of the study was to quantify the environmental impacts related to the EnerGAware game-based solution for domestic energy saving. The system boundaries included four life cycle stages: production (including all steps from material extraction to the assembly of all component devices), transport (from production sites to the configuration site and to the social housing pilot), functional use, and maintenance.

Two product systems were analysed: the EnerGAware pre-competitive solution and the EnerGAware market solution. The EnerGAware pre-competitive solution directly arises from the research project [15] and includes the game "Energy Cat: the House of Tomorrow" [16], the game server, the tablet provided to the tenants on which to run the game, the router, and the energy monitoring system installed in the pilot houses (Figure 4). Electricity consumption data were collected by attaching an optical pulse reader and a standard wireless M-Bus pulse counter to the existing electricity meter. Gas meter consumption data were gathered using an energy cam to read existing meter data and transform it into an M-Bus parameter. A data concentrator wirelessly read the electricity and gas consumption data and sent them to a remote server through a GPRS connection. The data concentrator cabinet, installed inside the pilot study houses, included a 24 V DC (60 W) power supply to feed the whole set, general electrical protection according to current UK safety regulations for electrical equipment, and wireless receptors to collect data from the wireless M-Bus readers attached to the gas and electricity meters. The data concentrator cabinet also included a data logger that can read and store the meter data and receive remote server requests, and a GPRS antenna to easily connect to the wireless network without coverage problems. Finally, a remote data server hosted a platform to facilitate configuration, maintenance, and monitoring tasks for the energy monitoring system. The server also parsed messages and displayed data through web services for further analysis. For the purpose of this life cycle assessment (LCA) study and according to the initial design of the pilot experiment, it was assumed that the game was played in 50 homes for one year, although after this period, tenants could still save energy.

The EnerGAware market solution considers the exploitation of the developed solution. In this case, the analysed system includes the game "Energy Cat: the House of Tomorrow" [5], the game server and the part of the tablet and router needed to play the game (Figure 5). In this scenario, the game is distributed freely by energy providers to their customers. In this case, players use their own mobile devices and energy metering data is collected from existing smart meters. According to Berg Insight [30], almost 40% of the 281 million electricity customers in Europe (EU28 + 2) had a smart meter by the end of 2017, and this percentage is set to increase to 70% in the next 5 years. It is therefore reasonable to assume that in this case, a dedicated energy metering system will not be needed as the game will be connected to existing smart meters. For the purpose of this LCA study and for ease of comparison and analysis, this scenario also considered 50 users and one year of useful life.

The functional unit was defined as the manufacturing and usage of the EnerGAware game-based solution for domestic energy saving over its lifetime.

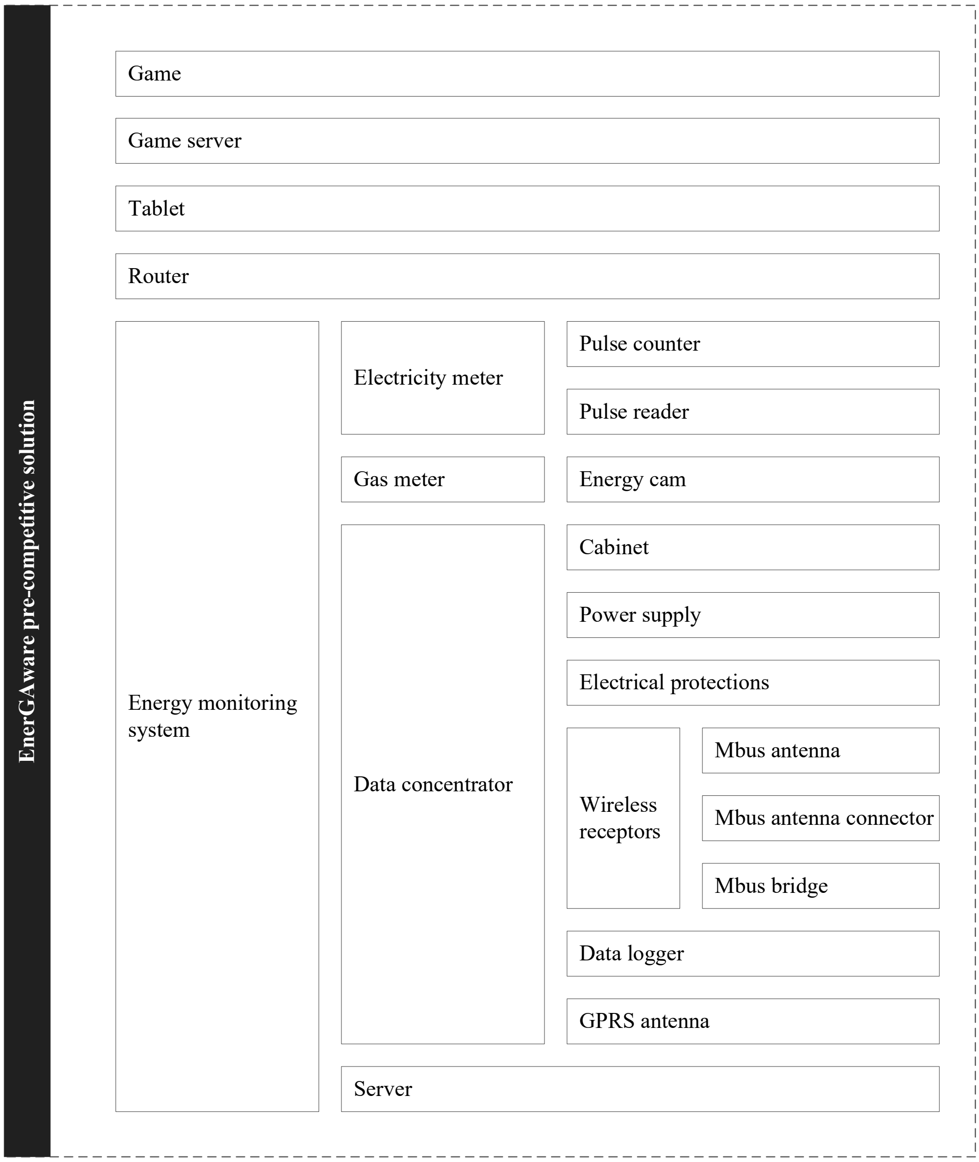

Figure 4. EnerGAware pre-competitive solution. Source: own elaboration.

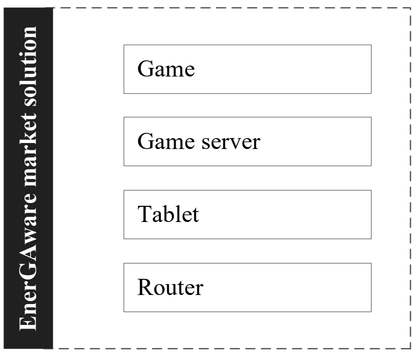

Figure 5. EnerGAware market solution. Source: own elaboration.

2.2. Inventory Analysis

The second stage of an LCA study involves the collection of data to quantify the material and energy inputs and outputs of the system. Table 1 summarizes the number of components in the EnerGAware pre-competitive solution and the EnerGAware market solution. Assumptions made in each lifecycle stage are detailed in the following subsections.

Table 1. Inventory analysis. Source: own elaboration.

	EnerGAware Pre-Competitive Solution	EnerGAware Market Solution
Game	1	1
Game server	1	1
Router	50	50
Tablet	50	50
Energy Monitoring System		
Data concentrator	50	0
Electricity meter	50	0
Gas meter	50	0
Monitoring system server	1	0

2.2.1. Production

According to the Grant Agreement [15], the game development involved 94 person months. Ninety percent of this effort was devoted to the production of the game, whereas the remaining 10% was devoted to later game updates. Therefore, the production of the game involved 12,125 desktop computer hours (office use) with a liquid crystal display, according to the Ecoinvent v3.4 database [31].

The game server and the router could be directly identified in the Ecoinvent v3.4 database [31]. However, both the tablet and the energy monitoring system had to be modelled by identifying and quantifying (mainly in terms of number and unitary weight) the main components and materials using the technical specifications of the pilot deployment plan [32], direct observation, and expert consultation. All the identified materials and components were linked to life cycle inventory data in the Ecoinvent v3.4 database [31]. Although this database contains specific data for some electronic components, electric materials, and products, some devices had to be modelled using unspecific, generic data.

In the EnerGAware pre-competitive solution, the impact of the production of electronic devices, including the game server, the tablet, the router, and the energy monitoring system, is completely allocated to the analysed system. In the EnerGAware market solution, the serious game is played on a pre-existing tablet using a pre-existing router. Therefore, production charges are allocated correspondingly according to the time spent by the player on the game under analysis, in relation to the total time spent using the tablet. According to pilot data [33], tenants play the game for an average of 15 min per week for three months. Assuming that a tablet is used for 90 min per day, charges allocated to the system are 0.55%. Considering that the game server hosts other games produced by the game developer, charges are correspondingly allocated. Energy Cat uses one-sixth of server resources and therefore only one-sixth of the impact of the production of the game server is assigned to both systems.

2.2.2. Transport

The game server is assumed to be transported from the production site to the premises of the project partner in charge of game development. The distance between Guangzhou (China) to Troyes (France) is assumed to be covered by 9501 km of aerial transport and 180 km of terrestrial transport.

The tablet is assumed to be transported from the production site (in Vietnam) to the pilot site (in Plymouth, UK), which involves 9240 km of aerial transport from Hanoi (Vietnam) to Heathrow airport (London, UK) and 360 km of terrestrial transport from Heathrow airport (London, UK) to Plymouth (UK).

The router is assumed to be transported from Guangzhou airport (China) to Plymouth (UK), which involves 9489 km of aerial transport and 360 km of terrestrial transport.

All the electronic devices in the energy monitoring system are transported from the production site (in China) to the premises of the project partner in charge of its configuration (Madrid, Spain). Afterwards, once the kits have been set up, they are sent to Plymouth (UK). This journey involves 10,400 km of aerial transport from Guangzhou airport (China) to Madrid airport (Spain), 20 km of terrestrial transport from Madrid airport (Spain) to the project partner premises (Spain), 20 km of terrestrial transport from the project partner premises (Spain) to Madrid airport (Spain), 1250 km of aerial transport from Madrid airport (Spain) to Heathrow airport (London, UK) and 360 km of terrestrial transport from Heathrow airport (London, UK) to Plymouth (UK). The energy monitoring system server, located in Madrid (Spain), is assumed to be transported from the production site (China), involving 10,400 km of aerial transport and 20 km of terrestrial transport.

In all cases, average data for aircraft freight transport and freight transport in lorries of 3.5–7.5 metric tons (EURO5) were taken from the Ecoinvent v3.4 database [31].

In the EnerGAware pre-competitive scenario, the impact of the transport of electronic devices including the game server, the tablet, the router, and the energy monitoring system is completely allocated to the analysed system. Within the EnerGAware market scenario, the serious game is played on a pre-existing tablet using a pre-existing router, and therefore transportation charges are allocated correspondingly according to the time spent by the player in the game under analysis in relation to the total time spent by the player using the tablet (see Section 2.2.1 for detailed information). The impact of transporting the game server is proportionally assigned to the EnerGAware market system, as the server hosts five other games as well. For the sake of simplicity, the EnerGAware market scenario is also assumed to be in Plymouth (UK).

2.2.3. Use

In accordance with data gathered in the Plymouth pilot [33], tenants played with the serious game for an average of 15 min per week, for 3 months. Therefore, in both the pre-competitive and market scenarios, the tablet is assumed to work for 180 min, although the lifespan is set to last one year. The game server is assumed to be active throughout the considered period, but the impact is shared among all the games hosted by the server. The Great Britain electricity mix (low voltage) and the French electricity mix (low voltage) taken from the Ecoinvent v3.4 database [31] are used to model the energy consumed by the tablet and the game server, respectively.

The energy monitoring system, including the server, is assumed to work 24 h per day for one year. The router is assumed to download meter readings three times a week for three months, with a total estimated duration of 36 min. Downloading the serious game at the beginning of the use phase is assumed to last two minutes. The router, the data concentrator, the electricity, and the gas meters are assumed to use the Great Britain electricity mix (low voltage) [31]. Considering that the server is in Madrid, the Spain electricity mix (low voltage) taken from the Ecoinvent v3.4 database [31] is used.

For the sake of simplicity, the Great Britain electricity mix (low voltage) taken from the Ecoinvent v3.4 database [31] is also used in the EnerGAware market scenario.

2.2.4. Maintenance

As already anticipated, the maintenance phase involves 1347 computer hours devoted to the development of game improvements. The router's energy consumption when these updates are downloaded is considered negligible. The maintenance phase also includes battery replacement activities for some energy management system devices in the EnerGAware pre-competitive scenario, particularly the energy cam and the wireless M-bus pulse counter. The replacement interval is assumed to be 12 years.

2.3. Impact Assessment

The environmental impact was computed using SimaPRO 8.5.2.0 [34], one of the most commonly used software applications for life cycle assessment, using the ReCiPe 2016 v1.02 midpoint and endpoint methods [35] with the hierarchist perspective. The midpoint approach is problem-oriented and focuses on 18 impact categories, each one measured with corresponding units. The endpoint approach is damage-oriented and groups the aforementioned impact categories into three damage categories, which makes it easier to understand the impact but increases uncertainty derived from the harmonisation of endpoint environmental categories into bigger groups.

2.4. Interpretation of the Results

The following subsections provide a comprehensive environmental profile of the EnerGAware pre-competitive solution and the EnerGAware market solution.

2.4.1. Environmental Impact of the EnerGAware Pre-Competitive Solution

Tables 2 and 3 and Figures 6 and 7 describe the results obtained for the EnerGAware pre-competitive solution, including the game "Energy Cat: the House of Tomorrow" [16], the game server, the tablet, the router, and the energy monitoring system.

Table 2 and Figure 6 show environmental impacts caused by manufacturing the various EnerGAware pre-competitive scenario components. The results revealed that the environmental impact related to the assembly phase of the EnerGAware pre-competitive scenario was mainly caused by the energy monitoring system (represented in red in Figure 6) with contributions ranging from 82.30% to 89.05% in the impact categories, except for terrestrial ecotoxicity (69.20%) and marine eutrophication (75.92%). According to the results, the impact of the monitoring subsystem can be mostly attributed to the electricity meters (representing between 61.20% and 70.48% of the impact of the energy monitoring system), followed by the data concentrators, which contribute between 27.81% and 36.30%. The impact of the game subsystem (represented in black in Figure 6) was found to range from 10.96% to 17.70%. Within this subsystem and in general (except for marine eutrophication), the router accounted for half the impact (46.66–67.39%), followed by the tablet (28.10–43.36%). Higher variability in contribution ratios was found for the game. As an example, the game was found to account for only 3.22% of the terrestrial ecotoxicity impact, but 22.14% of the ionizing radiation impact. The results show negligible contributions to all categories for the game sever (0.41–1.03%). The potential impact on human health caused by emissions associated with the EnerGAware pre-competitive scenario was found to amount to 0.21 DALY (one DALY unit equals the loss of one year of healthy life), whereas the potential impact on ecosystems was found to be 2.14×10^{-4} species·year (time integrated species loss), and the potential impact on resources accounted for 1764.70 USD2013, representing the extra costs involved for future mineral and fossil resource extraction. In all cases, the energy monitoring system accounted for most of the overall impact.

Table 3 and Figure 7 show the environmental impact of the EnerGAware pre-competitive solution until commissioning (including raw material acquisition, manufacturing, and transportation) and during the usage phase (including operation and maintenance). Most of the impact is attributed to the assembly phase (contributions range from 73.90% to 99.45%) and the remaining impact is distributed into the operational, transport, and maintenance phases.

The endpoint results are in the same vein (Figure 7). The assembly phase of the EnerGAware pre-competitive solution is responsible for 94.07% of the impact in the human health category, 87.44% in the ecosystem category, and 75.91% in the resources category. According to the results and from a life cycle perspective, the energy monitoring system accounted for most of the overall impact.

Table 2. Midpoint environmental impacts caused by manufacturing the various EnerGAware pre-competitive scenario components. Source: own elaboration.

Impact Category	Unit	Game System					Energy Monitoring System					Total
		Game	Game Server	Router	Tablet	Total	Data Concentrator	Electricity Meter	Gas Meter	Monitoring System Server	Total	
GWP	kg CO_2 eq [1]	334.60	32.70	1857.33	1365.55	3590.17	8732.24	16,847.03	317.02	196.17	26,092.47	29,682.64
SOD	kg CFC11 eq	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.02
IR	kBq Co-60 eq	81.84	2.19	181.73	103.88	369.64	777.19	1585.00	29.46	13.13	2404.77	2774.41
OFH	kg NO_x eq	0.74	0.09	5.62	3.72	10.16	23.27	48.42	0.93	0.52	73.14	83.30
PM	kg PM2.5 eq	0.66	0.08	5.58	4.42	10.74	20.35	37.09	0.88	0.49	58.80	69.54
OFT	kg NO_x eq	0.76	0.09	5.73	3.81	10.38	23.67	49.15	0.95	0.55	74.32	84.70
TA	kg SO_2 eq	1.50	0.15	12.63	10.13	24.41	41.20	69.47	1.95	0.89	113.51	137.92
FE	kg P eq	0.52	0.07	6.14	3.77	10.50	24.04	59.91	1.05	0.42	85.41	95.91
ME	kg N eq	0.10	0.01	0.21	0.39	0.69	0.69	1.43	0.03	0.03	2.19	2.88
TEC	kg 1,4-DCB	2152.72	274.29	45,040.79	19,371.85	66,839.65	93,631.07	49201.68	5676.10	1645.75	150,154.60	216,994.24
FEC	kg 1,4-DCB	75.11	11.22	1033.01	647.20	1766.54	3927.26	9932.38	175.37	67.30	14,102.32	15,868.86
MEC	kg 1,4-DCB	104.25	15.73	1464.62	908.04	2492.64	5541.22	13,964.09	248.12	94.40	19,847.83	22,340.47
HCT	kg 1,4-DCB	33.73	3.68	363.39	188.24	589.04	1052.13	2419.23	45.86	22.07	3539.29	4128.33
HNCT	kg 1,4-DCB	2219.96	365.13	35,645.11	21,228.69	59,458.88	134,335.38	340,467.35	6080.48	2190.76	483,073.97	542,532.85
LU	m^2a crop eq	11.72	0.93	59.15	54.97	126.77	238.46	472.76	11.47	5.59	728.28	855.05
MR	kg Cu eq	4.67	0.64	64.32	38.48	108.12	201.07	467.89	9.61	3.86	682.43	790.55
FR	kg oil eq	80.64	8.97	448.47	336.32	874.40	2101.66	4047.30	80.16	53.81	6282.93	7157.33
WC	m^3 [2]	3.82	0.24	16.35	11.68	32.10	72.38	123.30	3.05	1.43	200.16	232.25

[1] eq: equivalent. [2] m^3: cubic meter.

Table 3. Midpoint environmental impacts caused by the EnerGAware pre-competitive scenario components during their entire life cycle. Source: own elaboration.

Impact Category	Unit	Manufacturing			Transport			Use			Maintenance			Total
		Game System	Energy Monitoring System	Total	Game System	Energy Monitoring System	Total	Game System	Energy Monitoring System	Total	Game System	Energy Monitoring System	Total	
GWP	kg CO_2 eq [1]	3590.17	26,092.47	29,682.64	567.95	1622.08	2190.03	24.27	4481.16	4505.42	37.17	0.73	37.90	36,415.99
SOD	kg CFC11 eq	0.00	0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
IR	kBq Co-60 eq	369.64	2404.77	2774.41	8.60	19.48	28.08	245.60	693.75	939.34	9.09	0.07	9.16	3750.99
OFH	kg NO_x eq	10.16	73.14	83.30	2.37	6.94	9.31	0.05	8.36	8.41	0.08	0.00	0.08	101.10
PM	kg PM2.5 eq	10.74	58.80	69.54	0.59	1.53	2.12	0.05	6.71	6.76	0.07	0.00	0.08	78.49
OFT	kg NO_x eq	10.38	74.32	84.70	2.41	7.04	9.44	0.05	8.40	8.46	0.08	0.00	0.09	102.69
TA	kg SO_2 eq	24.41	113.51	137.92	1.68	4.65	6.34	0.11	19.16	19.27	0.17	0.01	0.17	163.70
FE	kg P eq	10.50	85.41	95.91	0.08	0.04	0.12	0.01	1.39	1.40	0.06	0.00	0.06	97.50
ME	kg N eq	0.69	2.19	2.88	0.01	0.00	0.01	0.01	0.10	0.11	0.01	0.00	0.01	3.01
TEC	kg 1,4-DCB	66,839.65	150,154.60	216,994.24	788.55	1514.21	2302.76	271.91	5491.73	5763.64	239.15	31.62	270.77	225,331.41
FEC	kg 1,4-DCB	1766.54	14,102.32	15,868.86	12.34	3.16	15.50	10.40	219.93	230.33	8.34	0.30	8.64	16,123.34
MEC	kg 1,4-DCB	2492.64	19,847.83	22,340.47	17.73	5.69	23.42	12.86	281.15	294.01	11.58	0.42	12.00	22,669.90
HCT	kg 1,4-DCB	589.04	3539.29	4128.33	7.19	10.15	17.34	2.68	148.37	151.05	3.75	0.12	3.86	4300.58
HNCT	kg 1,4-DCB	59,458.88	483,073.97	542,532.85	401.50	101.96	503.46	61.74	2200.20	2261.94	246.62	10.15	256.77	545,555.02
LU	m^2a crop eq	126.77	728.28	855.05	2.43	4.18	6.61	1.01	267.48	268.48	1.30	0.03	1.33	1131.46
MR	kg Cu eq	108.12	682.43	790.55	0.81	0.48	1.29	0.39	4.01	4.39	0.52	0.03	0.55	796.78
FR	kg oil eq	874.40	6282.93	7157.33	186.30	537.68	723.99	6.17	1134.12	1140.29	8.96	0.19	9.14	9030.75
WC	m^3 [2]	32.10	200.16	232.25	1.16	2.77	3.93	1.37	15.60	16.97	0.42	0.01	0.43	253.58

[1] eq: equivalent. [2] m^3: cubic meter.

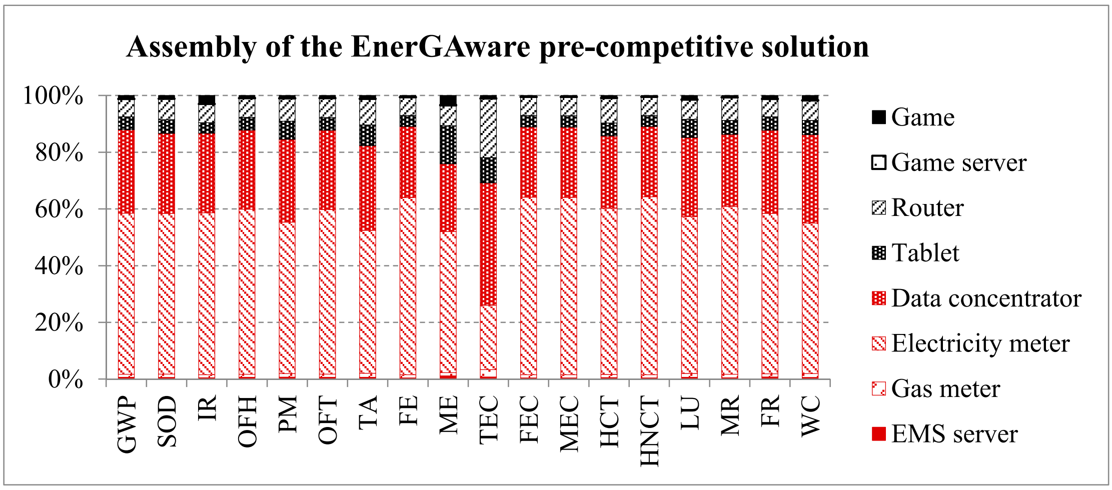

Figure 6. Midpoint environmental impacts caused by manufacturing the various EnerGAware pre-competitive scenario components. Source: own elaboration.

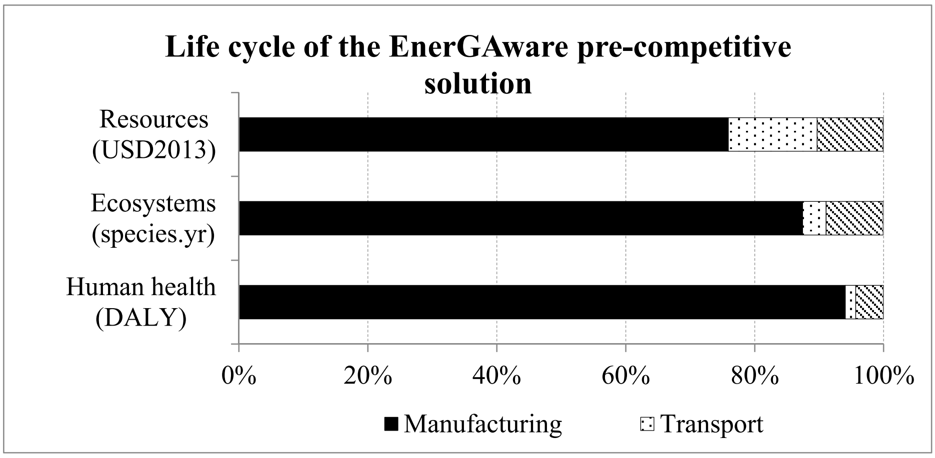

Figure 7. Endpoint environmental impacts caused by the EnerGAware pre-competitive scenario during its entire life cycle. Source: own elaboration.

2.4.2. Environmental Impact of the EnerGAware Market Solution

Table 4 and Figure 8 break down the environmental impact caused by manufacturing the various EnerGAware market scenario components. When it was considered that the game relies on existing smart meter infrastructure and is played on the user's own tablet, the environmental impact substantially decreased by between 96.39% and 99.47%, depending on the impact category. For example, the impact of global warming amounted to 384.96 kg of $CO_{2\ eq}$ for the EnerGAware market scenario, whereas the same impact was found to amount to 29,682.64 kg of $CO_{2\ eq}$ for the EnerGAware pre-competitive scenario. In all cases, the results revealed that most of the environmental impact related to the assembly phase of the Energy Cat game can be attributed to the game itself, with contributions ranging from 76.64% to 95.62%, followed by the game server (2.56–12.60%), the router (1.09–8.88%), and the tablet (0.67–4.02%) (Table 4 and Figure 8). In this case, damage to human health was found to amount to 1.66×10^{-3} DALYs, whereas damage to ecosystem quality amounted to 2.29×10^{6} species·year, and damage to resource availability was 19.98 USD2013. In all cases, the game accounted for most of the damage.

Table 4. Midpoint environmental impacts caused by manufacturing the various EnerGAware market scenario components. Source: own elaboration.

Impact Category	Unit	Game	Game Server	Router	Tablet	Total
GWP	kg CO_2 eq [1]	334.60	32.70	10.18	7.48	384.96
SOD	kg CFC11 eq	0.00	0.00	0.00	0.00	0.00
IR	kBq Co-60 eq	81.84	2.19	1.00	0.57	85.60
OFH	kg NO_x eq	0.74	0.09	0.03	0.02	0.88
PM	kg PM2.5 eq	0.66	0.08	0.03	0.02	0.79
OFT	kg NO_x eq	0.76	0.09	0.03	0.02	0.90
TA	kg SO_2 eq	1.50	0.15	0.07	0.06	1.78
FE	kg P eq	0.52	0.07	0.03	0.02	0.65
ME	kg N eq	0.10	0.01	0.00	0.00	0.10
TEC	kg 1,4-DCB	2152.72	274.29	246.80	106.15	2779.96
FEC	kg 1,4-DCB	75.11	11.22	5.66	3.55	95.53
MEC	kg 1,4-DCB	104.25	15.73	8.03	4.98	132.98
HCT	kg 1,4-DCB	33.73	3.68	1.99	1.03	40.43
HNCT	kg 1,4-DCB	2219.96	365.13	195.32	116.32	2896.72
LU	m^2a crop eq	11.72	0.93	0.32	0.30	13.28
MR	kg Cu eq	4.67	0.64	0.35	0.21	5.88
FR	kg oil eq	80.64	8.97	2.46	1.84	93.90
WC	m^3 [2]	3.82	0.24	0.09	0.06	4.21

[1] eq: equivalent. [2] m^3: cubic meter.

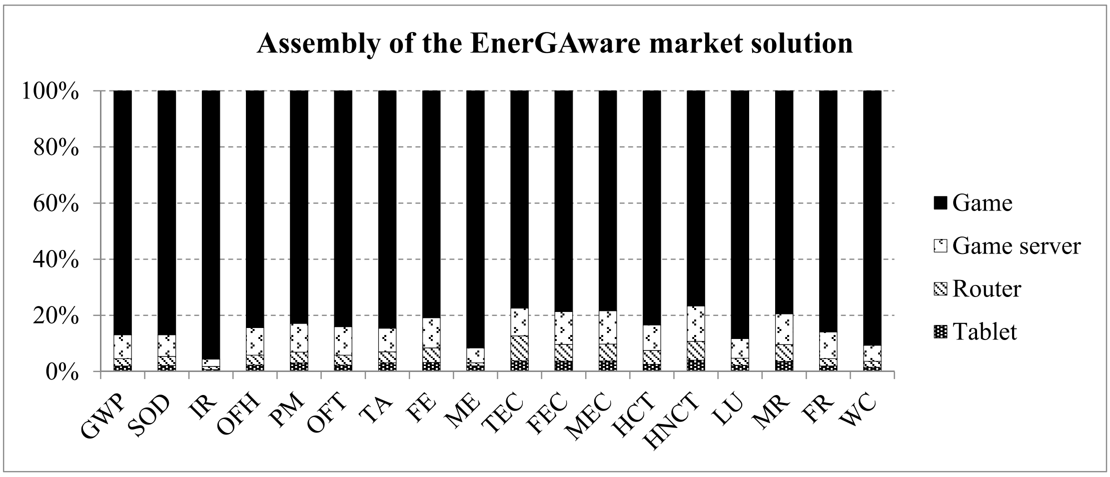

Figure 8. Midpoint environmental impacts caused by manufacturing the various EnerGAware market scenario components. Source: own elaboration.

Table 5 and Figure 9 show the life cycle environmental impact of the EnerGAware market scenario, including raw material acquisition, manufacturing, transportation, operation, and maintenance. Midpoint results show that, in general, the impact of the assembly phase represented between 67.38% and 83.07% of the total impact, except for ionizing radiation (24.99%), and the remaining impact was distributed into operational, transport, and maintenance phases.

From the endpoint perspective, most of the environmental impact was found to be in the manufacturing phase (80.12%, 79.82%, and 77.96% for damage to human health, ecosystems quality, and resource availability, respectively). Transport, use, and maintenance phases were found to contribute little to environmental impact. The transport phase was found to represent 8.78% of damage to human health, 7.57% of damage to ecosystem quality, and 8.86% of damage to resource availability, whereas the use phase amounted to 3.86% (damage to human health), 5.08% (ecosystems quality), and 5.82% (resource availability), and the maintenance phase represented the remaining 7.24%, 7.54%, and 7.36% for damage to human health, ecosystems quality, and resource availability, respectively.

Table 5. Midpoint environmental impacts caused by the EnerGAware market scenario during its entire life cycle. Source: own elaboration.

Impact Category	Unit	Manufacturing	Transport	Use	Maintenance	Total
GWP	kg CO_2 eq [1]	384.96	35.63	24.27	37.17	482.02
SOD	kg CFC11 eq	0.00	0.00	0.00	0.00	0.00
IR	kBq Co-60 eq	85.60	2.22	245.60	9.09	342.51
OFH	kg NO_x eq	0.88	0.10	0.05	0.08	1.11
PM	kg PM2.5 eq	0.79	0.08	0.05	0.07	1.00
OFT	kg NO_x eq	0.90	0.10	0.05	0.08	1.14
TA	kg SO_2 eq	1.78	0.16	0.11	0.17	2.21
FE	kg P eq	0.65	0.07	0.01	0.06	0.79
ME	kg N eq	0.10	0.01	0.01	0.01	0.13
TEC	kg 1,4-DCB	2779.96	277.11	271.91	239.15	3568.13
FEC	kg 1,4-DCB	95.53	11.22	10.40	8.34	125.50
MEC	kg 1,4-DCB	132.98	15.74	12.86	11.58	173.17
HCT	kg 1,4-DCB	40.43	3.70	2.68	3.75	50.56
HNCT	kg 1,4-DCB	2896.72	365.33	61.74	246.62	3570.41
LU	m^2a crop eq	13.28	0.94	1.01	1.30	16.53
MR	kg Cu eq	5.88	0.64	0.39	0.52	7.43
FR	kg oil eq	93.90	9.94	6.17	8.96	118.98
WC	m^3 [2]	4.21	0.24	1.37	0.42	6.25

[1] eq: equivalent. [2] m^3: cubic meter.

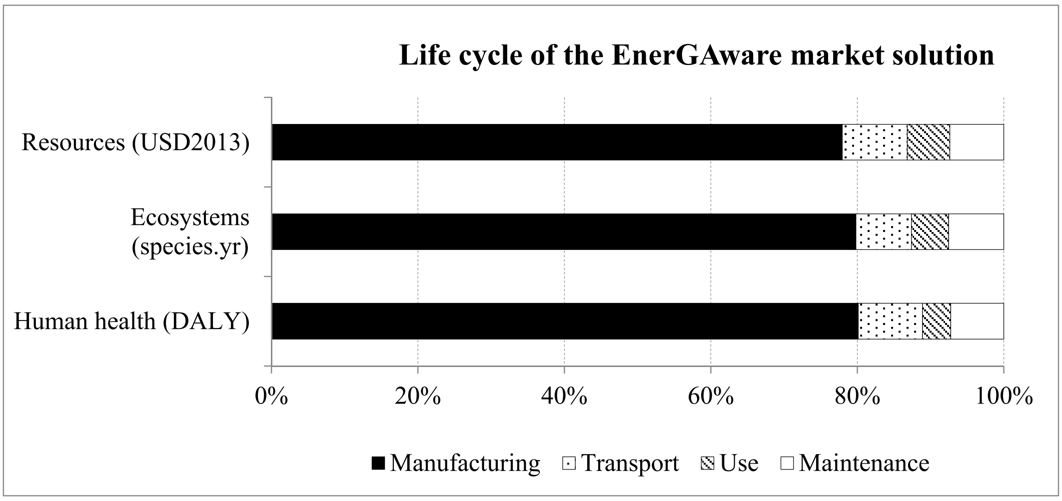

Figure 9. Endpoint environmental impacts caused by the EnerGAware market scenario during its entire life cycle. Source: own elaboration.

3. Discussion of the Results

As reported in previous sections, the pre-competitive solution was found to have a much greater environmental impact than the solution used outside of the research project in the context of the roll out of smart metering, mainly because the EnerGAware market solution is assumed to rely on a pre-existing tablet, router, and smart metering system infrastructure. In both cases, most of the impact is attributed to the manufacturing phase, and the remaining impact is distributed among operational, transport, and maintenance phases.

In the EnerGAware market scenario, most of the impact can be attributed to the production of the game itself. This paper analysed the effects of using the game for one year in a population of 50 houses. When the sample is extended, the impact related to the production of the game will diminish proportionally, whereas the energy saving of the game will have a multiplying effect. When the analysed period is extended, the effect of the production of the game will also be softened, and savings will be boosted. In fact, the useful life of a game-based solution is very difficult to predict because there is high uncertainty about how household savings will evolve in the future. Moreover, it must be considered that the electricity mix can change during the game's lifespan. Results may also be affected by advances in technology and obsolescence.

Besides the aforementioned considerations, the EnerGAware game-based solution for energy saving would be worthwhile if it could reduce the impact of the energy consumed by houses in the reporting period and the implemented solution, in relation to the impact of the energy consumed by houses in the baseline period (Figure 2).

Figure 10 summarizes the endpoint environmental impacts of the energy consumed by houses during the baseline and reporting periods using the EnerGAware pre-competitive scenario (left) and the EnerGAware market solution (right), considering that the game was implemented in 50 houses for one year. The results revealed that the EnerGAware pre-competitive scenario, which emerged directly from the research project, added significant environmental impact to human health (29.04%), ecosystems (10.06%), and resources (3.59%) in relation to the baseline situation (Figure 10). However, when use of the game outside of the research project was analysed, the results showed that the environmental impact in the reporting period was lower than in the baseline period. Reductions ranged from 3.68% for damage to human health, 3.87% for ecosystem quality, and 4.81% for resource availability (Figure 10).

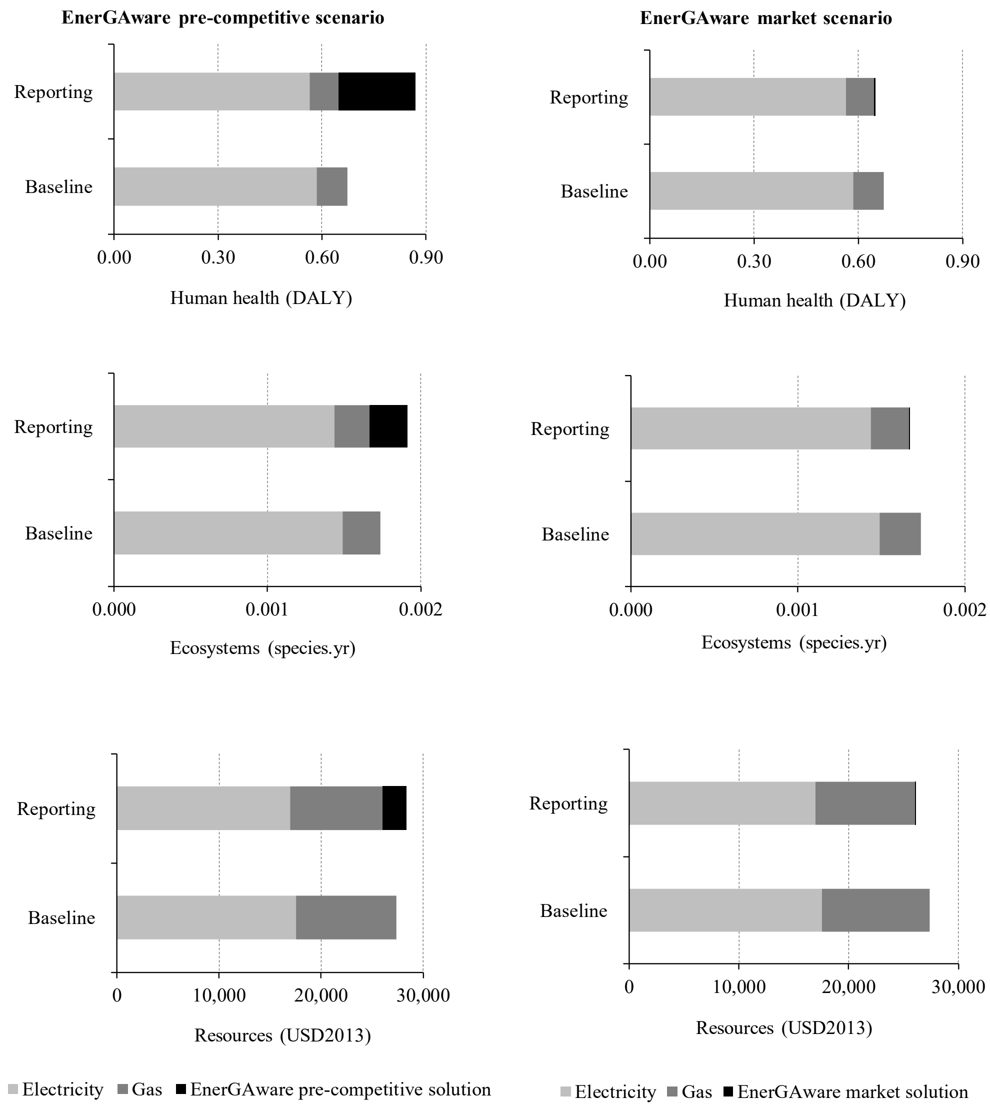

Figure 10. Endpoint environmental impacts of the energy consumed by houses during the baseline and reporting periods using the EnerGAware pre-competitive solution and the EnerGAware market solution. Source: own elaboration.

4. Conclusions

The results of this research provide an innovative insight into the life cycle environmental impact of a game-based solution for domestic energy saving developed within the EnerGAware project (Energy Game for Awareness of energy efficiency in social housing communities), funded by the European Union under the H2020 research program. For the purpose of this research, two main systems are analysed. The first focuses on the solution developed within the research project (in other words, the pre-competitive result), and the second analyses the solution within the context of the roll out of smart metering. In both cases, the game is assumed to be played by 50 users for one year. System boundaries included manufacturing (all steps from material extraction to the assembly of all component devices), transport (from production sites to the assembly site and to the pilot site), use, and maintenance. Life cycle impacts were calculated with SimaPRO 8.5.2.0 [34] using the ReCiPe 2016 v1.02 midpoint and endpoint methods [35] and the information contained within the Ecoinvent v3.4 database [31].

Under no circumstances should life cycle environmental impacts detract from environmental benefits in terms of sustained energy saving. However, according to the results of this research, future implementation of the game will allow significant reductions in the environmental impact of the energy consumed by houses, even when the life cycle impact of the game itself is considered. Therefore, the game will allow savings of 5.34% of the energy consumed by a household on average and will help to reduce the life cycle impact of domestic energy consumption on damage to human health (3.68%), ecosystem quality (3.87%), and resource availability (4.81%). The game is seen as an effective way to adjust to urban heat island effects without proportionally increasing the households' energy demand. However, further research is needed to ascertain how the game could interact with the local climate.

While it is beyond the scope of the present study, a full cradle-to-grave LCA should be conducted in the future to cover end-of-life scenarios. Improved life cycle inventory (LCI) databases are needed, as data quality and availability are serious challenges in life cycle assessment studies of ICT products [22].

As recognized by Nesticò and Maselli [36], it is important to provide decision makers with a complete profile of knowledge of the effects, both financial and extra-financial, that projects (or products) are expected to produce. However, environmental impacts are not always among the prioritized concerns of traditional decision making [37]. Life Cycle Assessment has been extensively used to get a comprehensive environmental profile of a product or service through the quantification of an extensive set of impact categories. As stated by Dong et al. [37], integrating LCA-based environmental impacts into existing Multi-Criteria Decision Making techniques is the best way to effectively support informed judgement on compared alternatives. Therefore, results described in this paper are highly useful for a range of stakeholders—including energy service providers, housing agencies, energy agencies, and other policy makers—as it prepares the ground for environmental benchmarking among competing energy-saving strategies.

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Nomenclature

E	Ecosystems
FE	Freshwater eutrophication
FEC	Freshwater ecotoxicity
FR	Fossil resource scarcity
GWP	Global warming
H	Human health
HNCT	Human non-carcinogenic toxicity
IR	Ionizing radiation
LU	Land use
ME	Marine eutrophication
MEC	Marine ecotoxicity
MR	Mineral resource scarcity
OFH	Ozone formation, human health
OFT	Ozone formation, terrestrial ecosystems
PM	Fine particulate matter formation
R	Resources
SOD	Stratospheric ozone depletion
TA	Terrestrial acidification
TEC	Terrestrial ecotoxicity
WC	Water consumption

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